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CA 2359445 A1 2003/04/03

(21) 2 359 445

(12) DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION

(13) A1

(22) Date de dépôt/Filing Date: 2001/10/03

(41) Mise à la disp. pub./Open to Public Insp.: 2003/04/03

(51) Cl.Int.$^7$/Int.Cl.$^7$ H04B 15/02, A61B 5/0402, H05K 9/00

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(54) Titre : FILTRE ANTI-PERTURBATION ELECTROMAGNETIQUE A BANDE ETROITE UNIVERSEL

(54) Title: UNIVERSAL NARROW-BAND EMI FILTER

(57) Abrégé/Abstract:

A new method of elimination of periodic or quasi-periodic noise is presented. Present method employs, as its main building block, a recently developed signal processing algorithm capable of extracting a specified component of a signal and tracking its variations over time. Performance of the present method is exemplified by application of the present EMI filter to elimination of power line noise potentially present on electrocardiogram and telephone cables. Superior performance of the method in terms of effective elimination of noise under frequency varying condition of power line signal is observed. Present method offers a simple and robust structure which complies with practical constraints involved in the problem such as low computational resources available and low sampling frequency.

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# UNIVERSAL NARROW-BAND EMI FILTER

## Abstract

A new method of elimination of periodic or quasi-periodic noise is presented. Present method employs, as its main building block, a recently developed signal processing algorithm capable of extracting a specified component of a signal and tracking its variations over time. Performance of the present method is exemplified by application of the present EMI filter to elimination of power line noise potentially present on electrocardiogram and telephone cables. Superior performance of the method in terms of effective elimination of noise under frequency varying condition of power line signal is observed. Present method offers a simple and robust structure which complies with practical constraints involved in the problem such as low computational resources available and low sampling frequency.

## Introduction

Power line interference coupled to signal carrying cables is particularly troublesome in medical equipment such as electrocardiograms (ECGs). Cables carrying ECG signals from the examination room to the monitoring equipment are susceptible to electromagnetic interference (EMI) of power frequency (50 Hz or 60 Hz) by ubiquitous supply lines and plugs so much so that sometimes the ECG signal is totally masked by this type of noise. Filtering such EMI signal is a challenging problem given that the frequency of the time varying power line signal lies within the frequency range of the ECG signal. There are some other technical difficulties involved, the most important of which is the low sampling frequency at which the ECG signals are taken and low computational resources available.

The history of attempts to mitigate power line EMI in ECG signals goes as far back as the ECG equipment itself. This problem was one of the first to attract the attention of developers of adaptive filtering theory [1]. Although classical adaptive filtering provides a partial solution to the problem, the problem is still considered open and research continues to find an ultimate solution [2, 3].

Pollution of ECG signals presents a general problem with medical equipment. This same problem may occur in a variety of other scenarios. For example, telephone lines carrying voice or data are subject to induced EMI from power lines both in the form of differential mode and common mode interference. While elimination of common mode EMI is trivial, in practice some residual differential mode interference always persists to exist. Presence of such differential mode EMI, frequency content of which lies within the frequency spectrum of the signal of interest, degrades the quality of the communication channel. The affected signal may be voice, or data in the case of telephone line-based data communications. The fact that characteristics of the interfering signal including its frequency may vary over time renders the noise suppression task difficult. Various methods of reduction of

power line interference have been proposed over the years each presenting strengths and weaknesses. No unique solution to this seemingly simple problem has been proposed so far [4]. Various signal processing schemes have been proposed in recent years for elimination of power line interference [3, 5].

A recently developed signal processing algorithm, introduced in [6] was found promising in construction of a universal EMI filter suitable for various applications in which the interference is a time-varying periodic (i.e. quasi-periodic) signal. It offers a robust structure and is shown to have a high degree of immunity with respect to external noise. This document presents structure and performance of such an adaptive EMI filter for the elimination of narrow-band interferences. Two examples of its application to ECG signals and signals carried by telephone lines are considered although the filter is general and may be applicable to other problems of similar nature.

## Review of the Core Unit

This section reviews the mathematical structure and properties of the core unit employed to construct the EMI filter of this invention. Let $u(t)$ denote a signal comprising a number of individual sinusoidal components and noise, expressed by

$$u(t) = \sum_{k=1}^{N} A_k \sin \phi_k + n(t) \tag{1}$$

where $\phi_k = \omega_k t + \theta_k$ is the total phase, and $n(t)$ denotes the total noise imposed on the signal. The objective is to find a scheme for estimating a certain component of such input signal as fast and accurate as possible; a scheme which should not be sensitive to the noise and the potential time variations of the input signal. Simplicity of the structure, for the sake of practical feasibility, is desirable.

Let $\mathcal{M}$ be a manifold containing all pure sinusoidal signals defined as

$$\mathcal{M} = \{y(t,\theta) = \theta_1 \sin(\theta_2 t + \theta_3) |\ \theta_i \in [\theta_{i,\min}, \theta_{i,\max}]\}$$

where $\theta = [\theta_1, \theta_2, \theta_3]^T$ is the vector of parameters which belongs to the parameters space

$$\Theta = \{[\theta_1, \theta_2, \theta_3]^T \mid \theta_i \in [\theta_{i,\min}, \theta_{i,\max}]\}$$

and $T$ denotes matrix transposition. To extract a certain sinusoidal component of $u(t)$, the solution has to be an orthogonal projection of $u(t)$ onto the manifold $\mathcal{M}$, or equivalently has to be an optimum $\theta$ which minimizes a distance function $d$ between $y(t,\theta)$ and $u(t)$, i.e.,

$$\theta_{\text{opt}} = \arg\min_{\theta\in\Theta} d(y(t,\theta), u(t)).$$

In least squares method, $d$ is the instantaneous distance function

$$d^2(t,\theta) = (u(t) - y(t,\theta))^2 \triangleq e(t)^2.$$

The parameter vector $\theta$ is estimated using the gradient descent method,

$$\frac{d}{dt}\theta(t) = -\mu\frac{\partial}{\partial\theta}(d^2(t,\theta))$$

where the positive diagonal matrix $\mu$ is the algorithm regulating constant. It controls the convergence rate as well as the stability of the algorithm.

Following the steps outlined above, a set of differential equations is obtained. The governing set of equations of this algorithms can be written as

$$\begin{aligned}
\dot{A} &= \mu_1 e \sin\phi, && (2)\\
\dot{\omega} &= \mu_2 e A \cos\phi, && (3)\\
\dot{\phi} &= \mu_3 e A \cos\phi + \omega, && (4)\\
y(t) &= A\sin\phi, && (5)\\
e(t) &= u(t) - y(t), && (6)
\end{aligned}$$

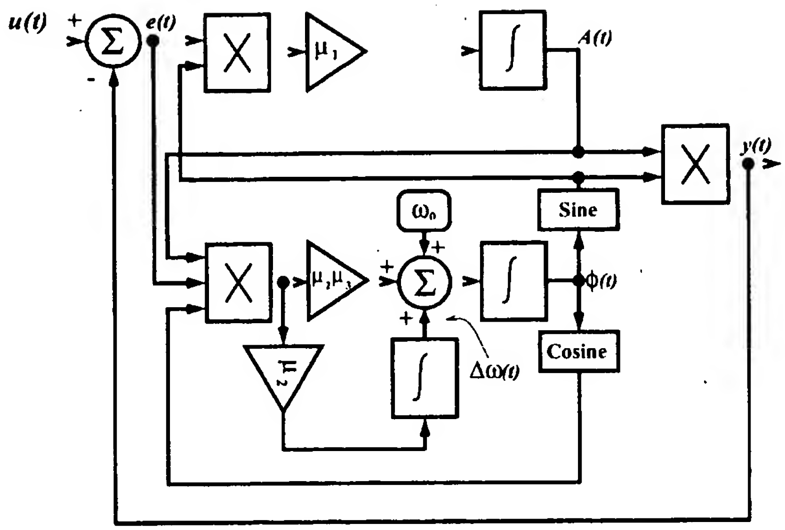


Figure 1: Block diagram implementation of the core unit.

where $y(t)$ is the output.

It has been shown that the dynamical system represented by the above set of differential equations possesses a unique asymptotically stable periodic orbit which lies in a neighborhood of the orbit associated with the desired component of the function $u(t)$. In terms of the engineering performance of the system, this indicates that the output of the system $y(t) = A \sin \phi$ will approach a sinusoidal component of the input signal $u(t)$. Moreover, time variations of parameters in $u(t)$ are tolerated by the system.

Figure 1 shows implementation of the algorithm in the form of composition of simple blocks suitable for schematic software development tools. Numerically, a possible way of writing the set of equations governing the present algorithm in discrete form, which can be readily used in any programming language, is

$$
\begin{aligned}
A[n+1] &= A[n] + T_s \mu_1 e[n] \sin \phi[n], \\
\omega[n+1] &= \omega[n] + T_s \mu_2 e[n] A[n] \cos \phi[n],
\end{aligned}
$$

$$\begin{aligned}\phi[n+1] &= \phi[n] + T_s\omega[n] + T_s^2\mu_2\mu_3 e[n]A[n]\cos\phi[n],\\ y[n] &= A[n]\sin\phi[n],\\ e[n] &= u[n] - y[n]\end{aligned}$$

where a first order approximation for derivatives is assumed, $T_s$ is the sampling time and $n$ is the index of iteration.

In the simulations presented in this document, Matlab Simulink™ computational software is used as the main computational tool. Figure 2 shows an example of performance of the core algorithm in which the frequency of the input signal undergoes a step change of 10%. It is observed that the variations are effectively tracked with a transient of few cycles. Values of the parameters are chosen to be $\mu_1 = 100$, $\mu_2 = 10000$, $\mu_3 = 0.02$, for this simulation.

The dynamics of the core algorithm presents a notch filter in the sense that it extracts (i.e. lets pass through) one specific sinusoidal component and rejects all other components including noise. It is adaptive in the sense that the notch filter accommodates variations of the characteristics of the desired output over time. The center frequency of such adaptive notch filter is specified by the initial condition of frequency $\omega$. In Figure 1 this initial value is explicitly shown for easy visualization.

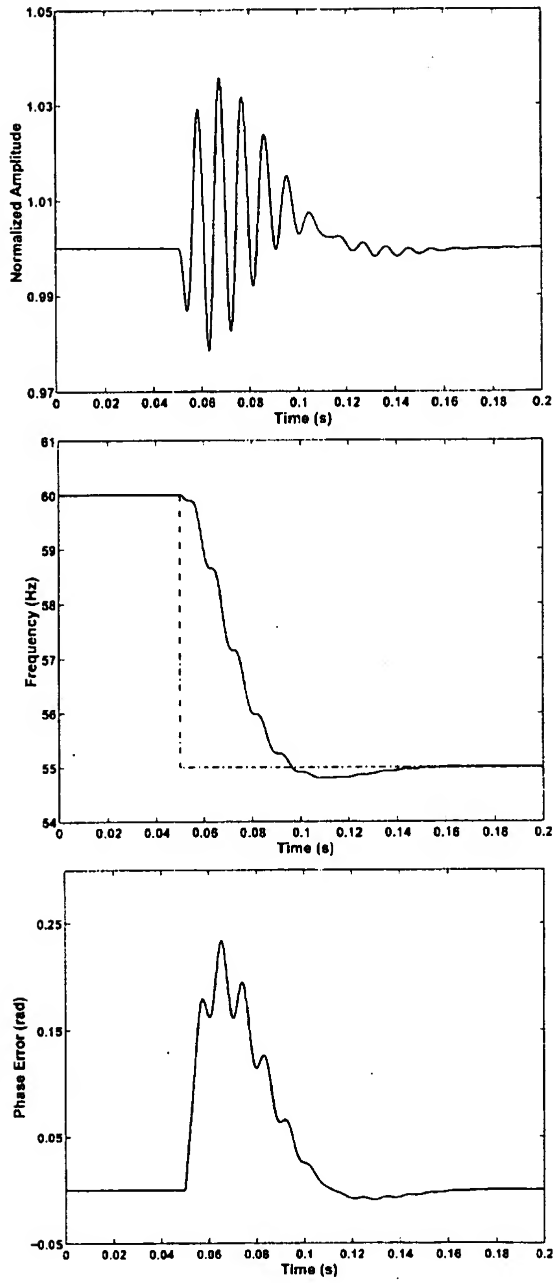


Figure 2: Response of the algorithm to a step change in the frequency of the input signal.

## Structure of the Present EMI Filter

One single unit of the core algorithm can be employed to extract the quasi-periodic interference mixed with the signal. This unit can effectively follow time variations in amplitude, phase and frequency of the interfering signal. Once it is extracted, it can be subtracted from the input signal to yield a clean signal.

In order to improve performance of the unit, the use of a band pass filter (BPF) to filter out non-interference signal components is proposed in Figure 3. This band pass filter does not need to be sophisticated and can be as simple as a second order filter. Its role is to improve the signal to noise ratio (signal here meaning the interference and noise meaning all other components) at the input of the core unit. Whatever is not removed by this BPF will be effectively removed by the core unit so as to produce a single pure sinusoid which is the interference. This interference in then to be subtracted from the input to provide the clean signal. BPF characterized by its transfer function $H(f)$ causes an attenuation $|H(f)|$ and phase delay $\angle H(f)$ which are functions of frequency. Since the core unit generates the value of the frequency in real-time, the attenuation and phase delays are known and can be restored as depicted in Figure 3. In general, the filter does not have to be band pass and a high pass filter may be sufficient. As a concrete example, the band-pass filter employed as the pre-filtering tool in Figures 3 and 4 is chosen to be a second order filter characterized by the following transfer function:

$$H(s) = \frac{100s}{s^2 + 100s + \omega_o^2}.$$

Gain and phase characteristics of this filter are shown in Figure 5 in which $\omega_o$ is taken to be 100 Hz for the ease of visualization.

Where the interfering signal is severely distorted, the harmonics may also be present. In such cases, desired signal is not polluted by a sinusoid, but by a number of sine waves. A

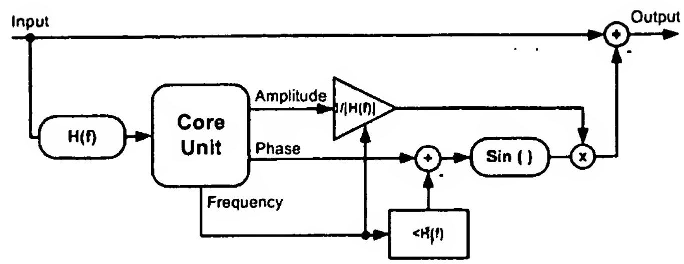


Figure 3: Block diagram of the present EMI filter.

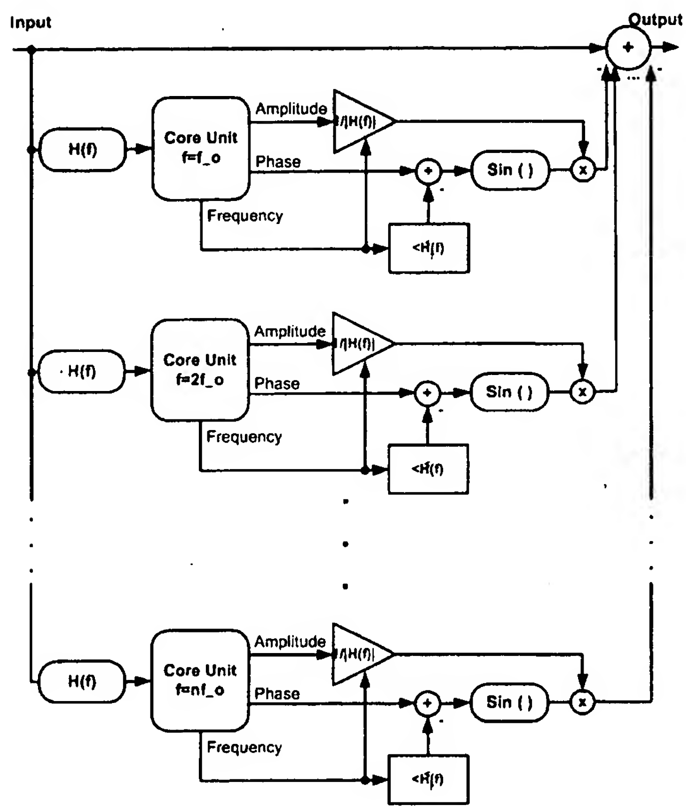


Figure 4: A configuration to eliminate a severely distorted quasi-periodic EMI.

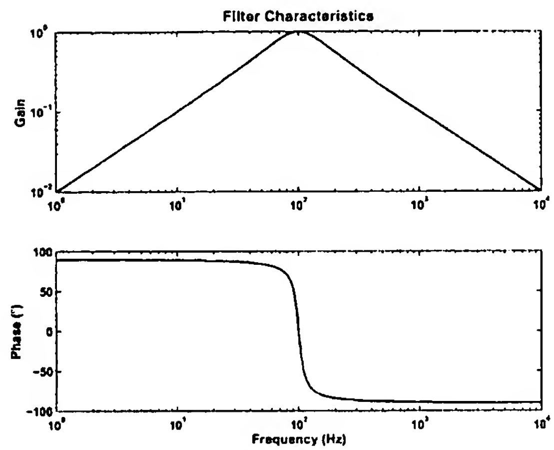


Figure 5: Gain and phase diagrams of the pre-filter.

more general configuration in Figure 4 may then be employed to eliminate the fundamental and the harmonics of the EMI.

## Application of the Present Filter to ECG Signals

ECG signal is basically an index of the functionality of heart. The physician can detect arrhythmia by studying abnormalities in the ECG signal. Since delicacies present in the ECG signal convey important information, it is important to have the signal as clean as possible. Figure 6 shows a clean ECG signal recorded at Beth Israel Hospital (BIT) in Boston and made available by Massachuset Institute of Technology MIT-BIH [7]. The recording was done using battery operated ECG equipment to minimize power line EMI although some such EMI still exists which is mostly coupled at the time of recording the signals on the tape. The frequency spectrum of this signal spans from near DC frequencies to about 100 Hz. The sampling frequency in most ECG devices are 240 Hz or 360 Hz. In this case, the equipment was operated at the sampling rate of 360 Hz.

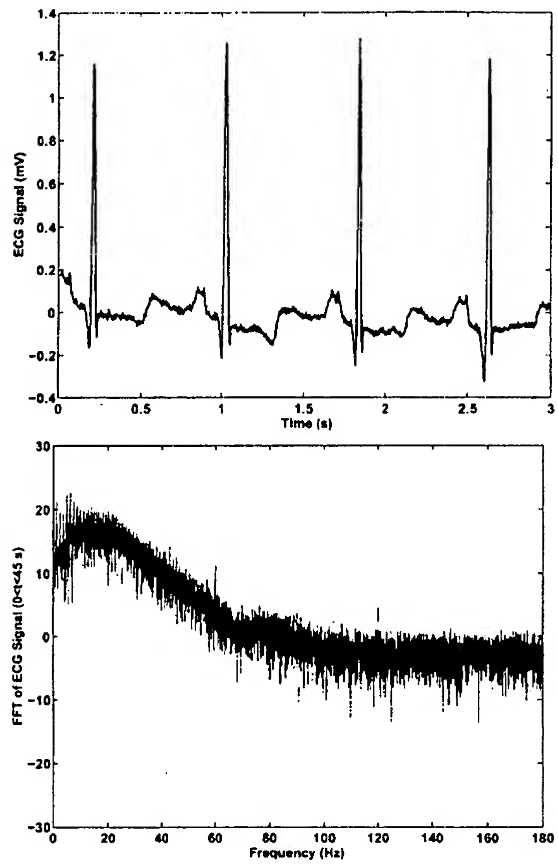


Figure 6: Recorded ECG signal and its frequency spectrum.

Therefore, the spectrum can theoretically include frequencies from zero to 180 Hz. The data available from MIT-BIH contains a high DC offset which is eliminated in simulations of this document.

ECG signals can be easily polluted by power line noise of relatively large amplitude. Were the frequency of power line interference accurately at 50 Hz or 60 Hz, a sharp notch filter would be able to separate and eliminate the noise [8]. The major difficulty is that the frequency can vary about fractions of a Hertz, or even a few Hertz in some countries. The

sharper the notch filter is designed, the more inoperative, or rather destructive, it becomes if any change in the frequency of the power line occurs. Of course, turning the notch filter into a band stop filter by widening its rejection band, and thereby accommodating frequency variations, does not offer any better solution since it will undesirably distort the ECG signal itself. The frequency of the power grid is usually taken as being constant when conventional EMI filters for ECGs are designed. In such arrangements, the system is very fragile with respect to power frequency variations and can become completely malfunctioned. Such adaptive or non-adaptive filters, those discussed in [9] for instance, greatly suffer from this shortcoming.

One of the possible alternatives to take frequency variations into account is the use of external reference power line signal [10]. This technique, available by the use of adaptive filters only, is reported practically difficult or rather impossible [9]. For this reason, other methods, usually very complex and inflexible, are constantly being proposed [2, 3].

The ideal EMI filter for ECG is the one which acts as a sharp notch filter to eliminate only the undesirable power line interference while automatically adapting itself to variations in the frequency of the noise. Of course, this adaptation must be done very quickly so as to keep the signal clean all the time. It is supposed to be able to work in low information background, namely that dictated by low sampling frequency, and must be robust with respect to variations in its internal as well as external conditions. An example of internal condition is its settings. External conditions can range from the temperature of the environment in which the equipment is supposed to function to the superimposed noise/distortion on the interfering power signal.

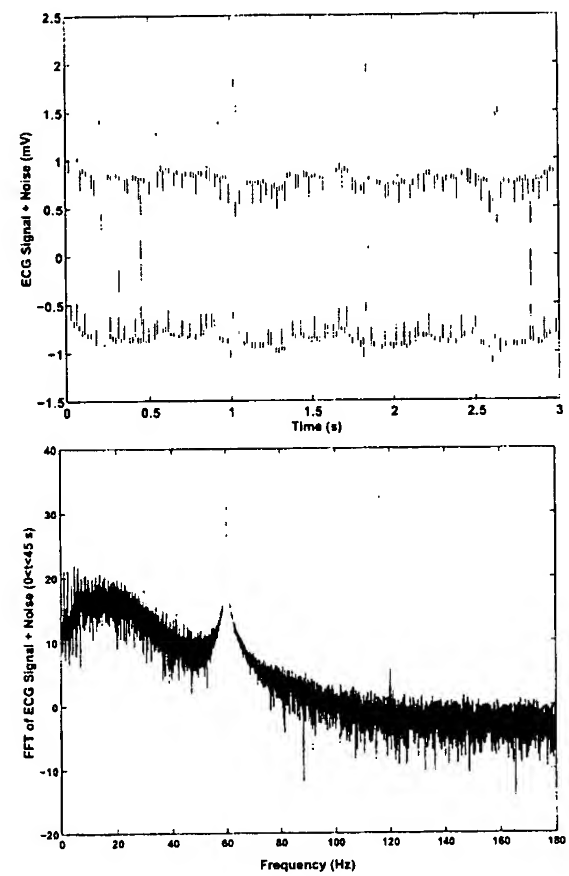


Figure 7: A power line interference of 1 mv level at 60 Hz is added to the ecg signal to provide a polluted input signal for the present filter.

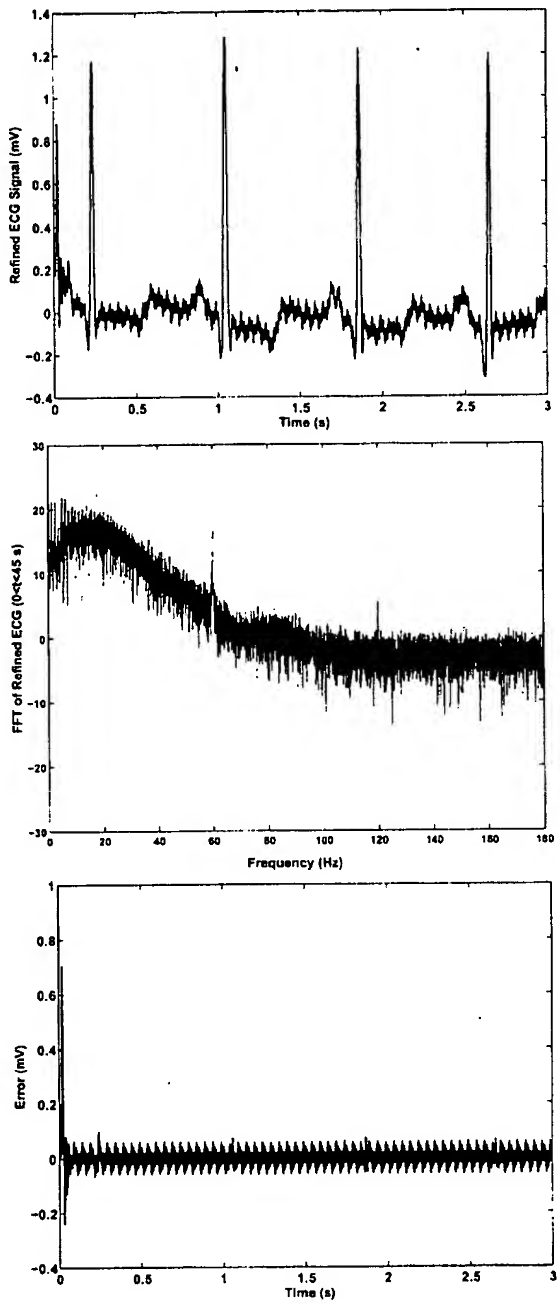


Figure 8: Performance of the filter in eliminating a power line interference of 1 mv level at 60 Hz.

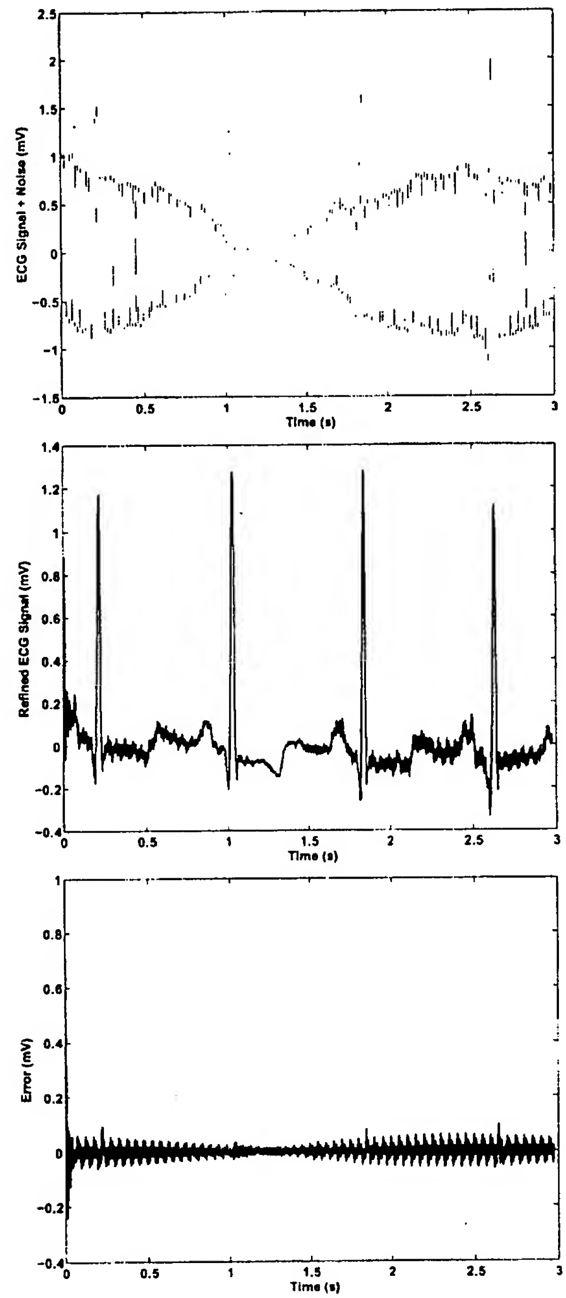


Figure 9: Performance of the filter in eliminating power line interference of time varying level (oscillating between 0 to 1 mv) at 60 Hz.

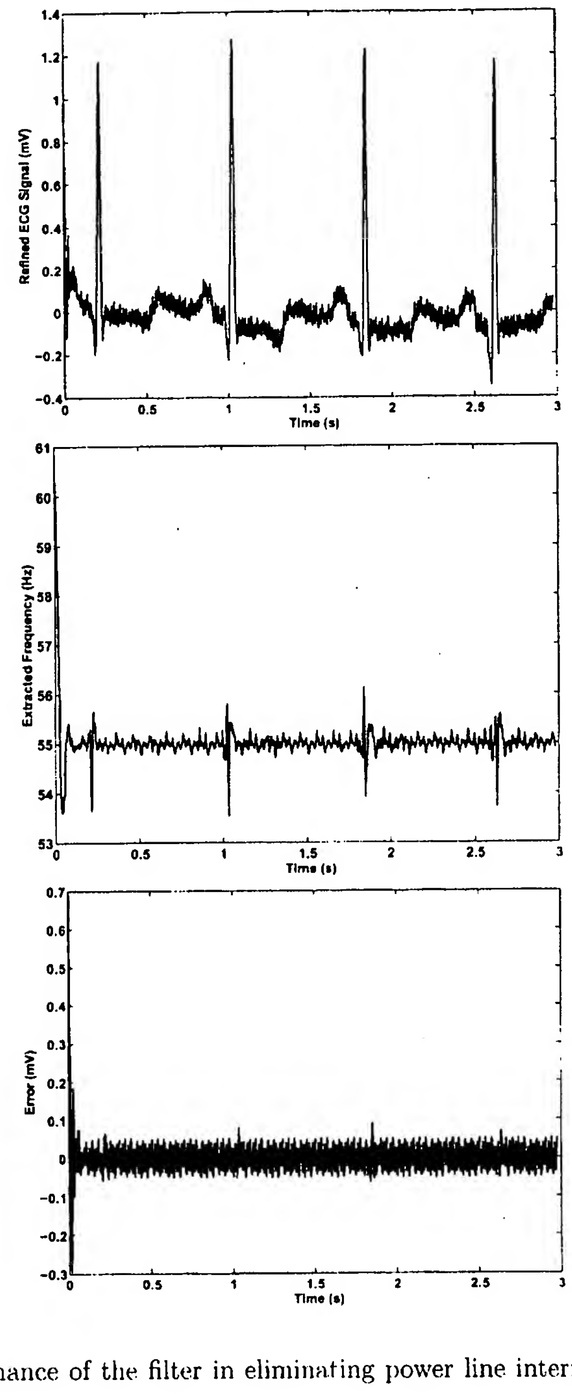


Figure 10: Performance of the filter in eliminating power line interference of 1 mv level at 55 Hz.

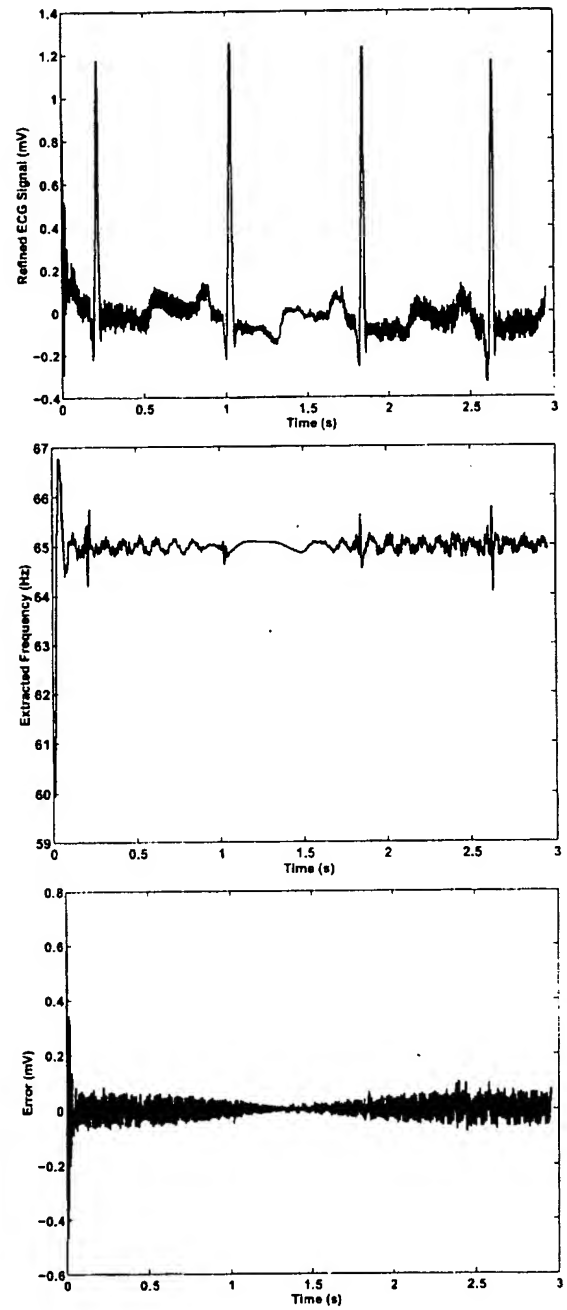


Figure 11: Performance of the filter in eliminating power line interference of time varying level at 65 Hz.

## Performance of Present EMI Filter in the Case of ECG Signals

This section presents a number of simulations to demonstrate performance of an EMI filter constructed as in Figure 3. The filter at the input of the core unit attenuates the ECG signal by a factor of 10. Figures 7 and 8 show performance of the filter in eliminating a power line interference of 1 mv constant level whose frequency is fixed at 60 Hz. This is an elementary experiment since a simple notch filter will easily eliminate such a fixed frequency noise. In the simulation, only a 60 Hz component is added to the clean ECG signal obtained from MIT-BIH [7] whose presence is clear in the frequency spectrum of the input (Figure 8).

The values of the parameters $\mu_1$, $\mu_2$, and $\mu_3$ determine the convergence speed versus error compromise. Generally, the higher the values are chosen, the faster the algorithm tracks variations at the expense of larger steady state error. Therefore, it is important to define desirable balance of speed/error. For the simulations in this document, a moderate choice of $\mu_1 = 200$, $\mu_2 = 20000$, and $\mu_3 = 0.01$ results in an EMI reduction of a factor of about 20 while keeping the transient time short enough. All initial conditions of integrators are zero except for that of frequency which is taken to be 60.

To demonstrate the ability of the filter in adaptively tracking the variations of the level of noise, the level of the EMI is made to be changing with time in Figure 9. Again, error is confined to within about $\frac{1}{20}$ of the maximum noise in the input.

Figure 10 shows performance of the filter in tracking the variations in frequency of the power line noise. The filter is adjusted -by virtue of its initial conditions- to extract a power line noise of frequency 60 Hz. The EMI in the input, however, is oscillating at 55Hz. Effective tracking of unknown input frequency is observed.

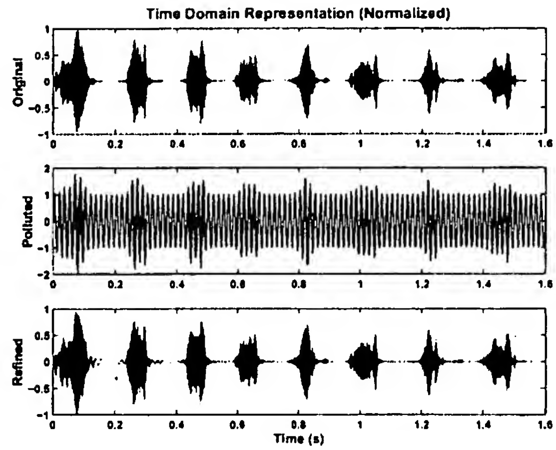


Figure 12: Time-domain representation of the performance of the present EMI eliminator in suppression of a fixed frequency interference from an arbitrary input signal.

Finally, Figure 11 shows performance of the filter when all characteristics of the EMI are changing with time. As before, the filter is adjusted to extract a power line noise of 60 Hz. However, the incoming EMI has a frequency of 65 Hz. The level of the EMI is also changing with time. Again, effective elimination of superimposed EMI is observed.

## Performance of Present EMI Eliminator in the Case of Telephone Line Signals

Figure 12 shows performance of the EMI filter in suppression of an interference of fixed frequency of 60 Hz from an arbitrary input signal. The original input signal is arbitrarily taken as a recorded bird chirp sampled at $F_s = 8192$ Hz. It goes without saying that the notch filter targets the pre-specified sinusoidal interference present in its input, hence frequency composition of the incoming signal is irrelevant as far as EMI filter is concerned. The level of interference added to the original signal is taken to be equal to that of the

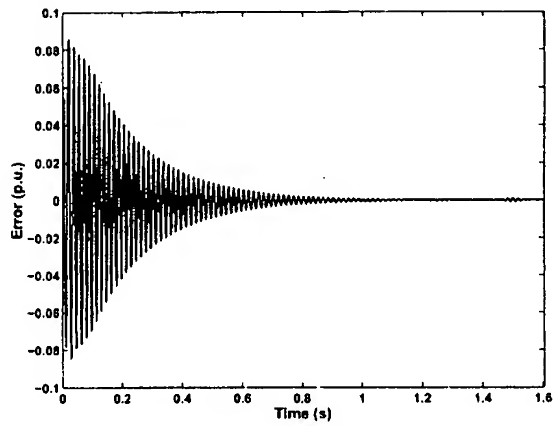


Figure 13: Error incurred in suppression of a fixed frequency interference from an arbitrary input signal.

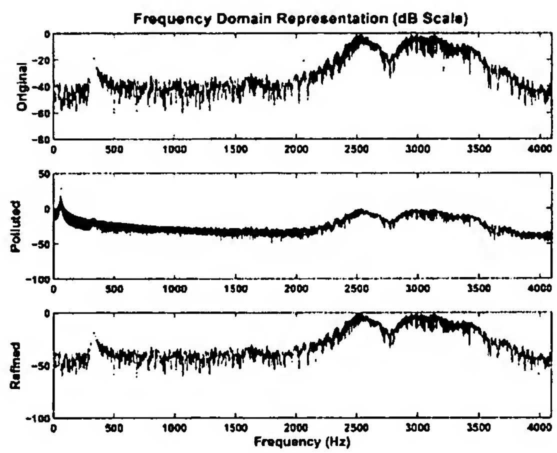


Figure 14: Frequency-domain representation of the performance of the present EMI eliminator in suppression of a fixed frequency interference from an arbitrary input signal.

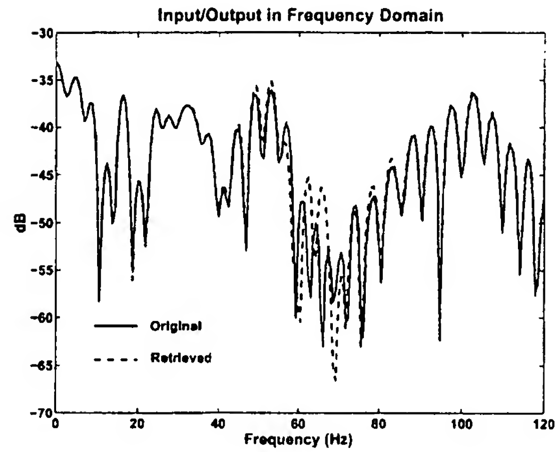


Figure 15: Magnified spectrum of the original and retrieved signals around the frequency of the interfering sinusoid (60 Hz).

original signal so that signal to noise ratio (SNR) is 0 dB in the following simulations. Figure 13 shows the incurred error in removing the EMI. It is basically the difference between the refined signal and the original signal not yet polluted by the interference. Frequency spectrums of the original, polluted and retrieved signals are shown in Figure 14. Figure 15 shows the magnified portion of the frequency spectrum of the original and the retrieved signals about the frequency of the interference. It is observed that the notch filter effectively removes the interference and retains the original signal almost untouched.

To show the adaptive nature of the present interference eliminator with respect to variations in frequency of the interfering signal, performance of the present method when a step change in the frequency of interference occurs is shown in Figure 16. As noted before, the rate of convergence in tracking time-variations such as that shown in Figure 16 is totally controllable by means of adjustment of parameters. The tracking capability of the present method is advantageous in devising a universal power supply noise eliminator independent of the nominal frequency of the grid. Regardless of initial frequency setting (whether 50 Hz or 60 Hz), the filter finds the instantaneous frequency of the power line

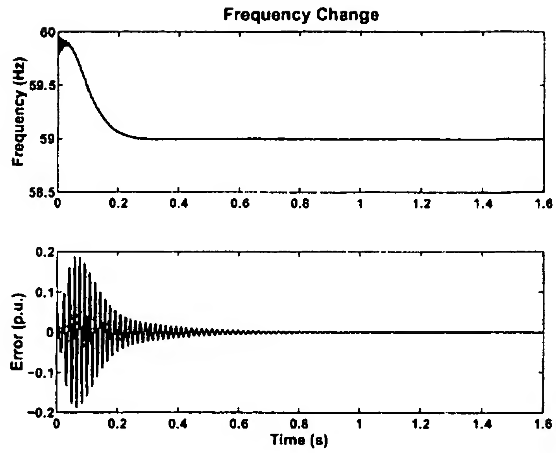


Figure 16: Response of the present method to a frequency step change in the interfering sinusoid. Top figure shows the estimated frequency and the bottom figure shows the incurred error in EMI suppression.

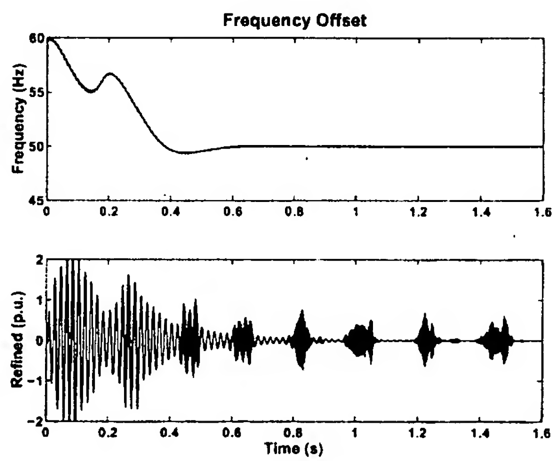


Figure 17: Response of the present method to a large frequency offset in the interfering sinusoid. Top figure shows the estimated frequency and the bottom figure shows the retrieved signal.

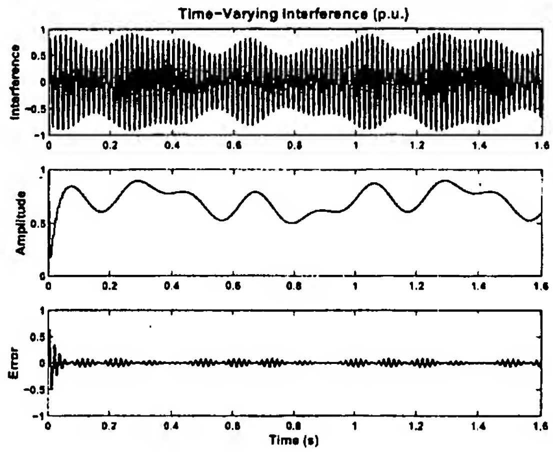


Figure 18: Performance of the present method in eliminating a sinusoidal interference of time-varying amplitude. The top figure is the interference, the middle figure is the estimated value of the amplitude of the interference and the bottom figure is the incurred error in EMI suppression.

interference. Figure 17 shows an example in which the EMI filter expects a 60 Hz power supply interference while the interference happens to be of 50 Hz frequency.

To demonstrate adaptive nature of the present method in tracking variations in the level of the interference, performance of the present method in eliminating an interference of time-varying amplitude is shown in Figure 18.

As noted before, power supply interference may be distorted by the presence of harmonics. Figure 19 shows an example of a highly distorted interference in which harmonics of third and seventh order are present. In such cases, a multiplicity of EMI filters, connected in parallel combination as suggested by Figure 4, may be used for EMI mitigation. Figure 20 shows the frequency domain representation of the performance of an EMI filter consisting of three units connected in parallel. The fundamental frequency of the interference is made to slightly vary over time. An EMI reduction of about 40 dB is observed. Again,

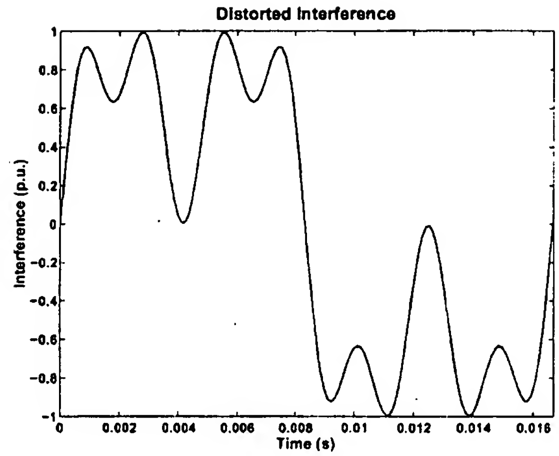


Figure 19: Interference is taken to be highly distorted by the presence of harmonics. This figure shows one cycle of the interfering signal.

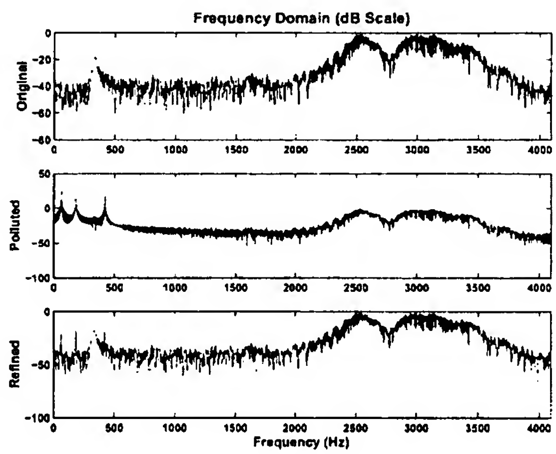


Figure 20: Frequency domain representation of the performance of the present method in elimination of interference of highly distorted shape. An EMI reduction of about 40 dB is observed.

the level of desired EMI mitigation is controllable by the adjustment of parameters and at the expense of speed. Considering that the power supply noise is usually a slowly time-varying signal, one can sacrifice speed for better interference elimination.

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